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Integrating radar and laser-based remote sensing techniques for monitoring structural deformation of archaeological monuments

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ABSTRACT

Ground-Based Synthetic Aperture Radar Interferometry (GBInSAR) and Terrestrial Laser Scanning (TLS) were purposely integrated to obtain 3D interferometric radar point clouds to facilitate the spatial interpretation of displacements affecting archaeological monuments. The paper describes the procedure to implement this integrated approach in the real-world situations of surveillance of archaeological and built heritage. Targeted tests were carried out on the case study of the Domus Tiberiana sited along the northern side of the Palatino Hill in the central archaeological area of Rome, Italy, and displacements of the monument were monitored over almost one year of acquisition. The GBInSAR – TLS integration provided updated information about the condition of the archaeological structures in relation to their history of instability mechanisms, and did not highlighted a general worsening for the stability of the entire monument. Point-wise and prompt detection of displacement anomalies and/or sudden changes in displacement trends proved the suitability of the method to support early warning procedures, also to evaluate effects on the masonry due to human activities.

1. Introduction

Remote sensing technologies are increasingly becoming useful tools for on site preservation of cultural heritage and to constantly update the condition report of a monument. Benefits can be obtained both in situations of ordinary maintenance and emergency surveys. Undertaking preventive diagnostics and monitoring campaigns, i.e. before the execution of any restoration work, is nowadays a sustainable strategy to identify the typology of ongoing deterioration processes and understand the triggering factors (UNESCO, 2010; Fanti et al., in press; Tapete et al., 2012, in press).

Conventional structural monitoring techniques, such as topographic surveys and measurements by means of wall mounted instruments, are still widely used. Nevertheless, such methods only provide point-wise information. Installation might also be a constraint, especially if the condition of the monument to monitor does not allow it or there is a risk for operators' safety. Conversely, ground-based remote sensing techniques can allow these limits to be overcome, thanks to their capability of measuring parameters without a physical contact with the interest object (i.e. non-invasiveness). Also, all the analytical steps – from acquisition phase to automatic data processing – can be managed remotely.

Among the radar-based techniques, Ground-Based Synthetic Aperture Radar Interferometry (GBInSAR) has been hugely tested in environmental applications, for instance to monitor the displacement field of landslide bodies (Antonello et al., 2004), volcanic flanks (Casagli et al., 2010), dynamics of glaciers (Luzi et al., 2007) and instability in mining areas (McHugh et al., 2006). First application for architectural purposes dated in the early 2000s, when the GBInSAR was exploited by the Joint Research Centre (JRC) to monitor the 1:1 scale reproduction of the façade of Palazzo Geraci, in Palermo, Italy. Further advances followed in these last years, and different technologies were developed, including the GBInSAR Lisamobile tested in the present work.

As an imaging technique, the GBInSAR offers the possibility to monitor natural and artificial surfaces with extent up to a few square kilometres, with high sampling frequency of displacement data (up to 1 image every few minutes), sub-millimetre accuracy and metre spatial resolution. The latter parameter is undoubtedly essential to distinguish architectural elements being affected by instability processes from the stable ones.

To overcome the limits of two-dimensional displacement maps, recent works have demonstrated the advantage of projecting the GBInSAR data on Digital Elevation Model (DEM) and Digital Terrain

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Model (DTM) generated from LiDAR point clouds reproducing the observed scene (Gigli et al., 2011; Luzi et al., 2009; Pieraccini et al., 2006). While Airborne Laser Scanning (ALS) is suitable for topographic survey of huge natural environments and for wide-area archaeological investigations (Lasaponara et al., 2010; Lasaponara and Masini, 2011), Terrestrial Laser Scanning (TLS) was found more adaptable for acquisition of the three-dimensional geometry of single monuments or group of buildings (Gigli et al., 2009). Non-invasiveness, reduced acquisition times, high accuracy and spatial resolution have opened to an extensive use of TLS in the field of cultural heritage, making it a routine device for architectural and archaeological documentation and building rendering (English Heritage, 2007; Lerma et al., 2010; Yastikli, 2007). TLS 3D models constitute optimal geometric supports for a more precise localization of the monitoring measures within the x–y–z space, allowing an immediate georeferencing of the superficial deformation detected over the monitored monuments.

Although the final outputs of the two techniques substantially differ in the dimensional configuration of the information provided (2D for GBInSAR data, 3D for TLS models), their integration is useful to improve the quality and reliability of monitoring campaigns on monuments and historical buildings.

In this paper we propose a non-invasive methodology integrating GBInSAR and TLS data to perform real-time monitoring of superficial deformation affecting archaeological and built heritage. After an overview of both the techniques, all the operational phases of GBInSAR – TLS integration are illustrated, starting from the preliminary choice of the site for the instrumentation installation to the processing of the final mapping output (the so-called "3D interferometric radar point clouds and models"). The results obtained during the monitoring campaign of the Domus Tiberiana within the central archaeological area of Rome, Italy, are here presented to critically discuss potentials and limits of this methodology, with specific regard to capabilities for activities of daily surveillance and warning in archaeological contexts.

2. The tested techniques

2.1. Ground-based radar interferometry (GBInSAR)

Synthetic Aperture Radar Interferometry (InSAR) is a non-invasive imaging technique which allows the detection of superficial deformation affecting natural and artificial environments/objects, based on the calculation of the phase difference of the collected radar signal between two SAR images covering the same scenario.

The active radar sensor is installed on a ground-based platform (that guarantees the ideal condition of zero baseline geometry) and it is equipped with two antennas. One transmits pulsed microwaves and one receives the echo backscattered by surfaces of the observed object, while the sensor moves along a linear rail of a certain length (usually 1–3 m; Fig. 1a). This configuration allows the acquisition of radar images of the observed scene following the principle of Synthetic Aperture Radar (Rosen et al., 2000), with generation of topography-free interferograms and quantitative estimation of the occurred displacement for each point (Tarchi et al., 2003). Each SAR image collected at a certain time is a two-dimensional map of the observed scene obtained by combining the spatial resolution along two directions: (i) the range resolution (ΔRr), along the direction perpendicular to the rail; (ii) and the azimuth resolution (or cross-range; ΔRaz), parallel to the synthetic aperture (Luzi, 2010; Fig. 2a).

Under the conditions of zero baseline and negligible decorrelation due to propagation and scattering phenomena (i.e. coherence value approximately of 1), the interferometric phase is directly related to the variation of the sensor-target distance. It means that the displacements occurred during the time elapsed between two or more subsequent coherent SAR acquisitions, can be effectively estimated along the Line Of Sight (LOS) of the radar sensor (Fig. 1b).

According to the specific acquisition geometry, only the component along the LOS (D_{LOS}) of the real displacement vector (D) can be estimated. Displacements along a direction parallel to the LOS are better estimated (D_{LOS} is equal to D), while those along perpendicular direction are missed (D_{LOS} is zero) (Fig. 1b).

This is one of the major limits of the technique. Hence, the choice of the installation site is essential and frequently requires a preliminary evaluation of the expected major directions of displacement. On the other hand, the high portability of the current models of GBInSAR instrumentation allows best acquisition geometry to be set up, thereby approaching the ideal condition of parallelism between the LOS and the hypothesized direction of the major vector component of the displacement.

Regarding the sensitivity, the radar operates at microwave frequencies ranging from 12 to 18 GHz and corresponding wavelengths of 2.50–1.67 cm (K_u band, according to IEEE Std 521–2002), and can ensure millimetre up to sub-millimetre accuracy.

Objects up to few square kilometres of extent can be monitored from distances up to thousand of metres. Although the cross-range resolution of SAR images varies within the observed scene due to the measurement distance, good acquisition geometries can lead to fine resolution in range better the 1 m.

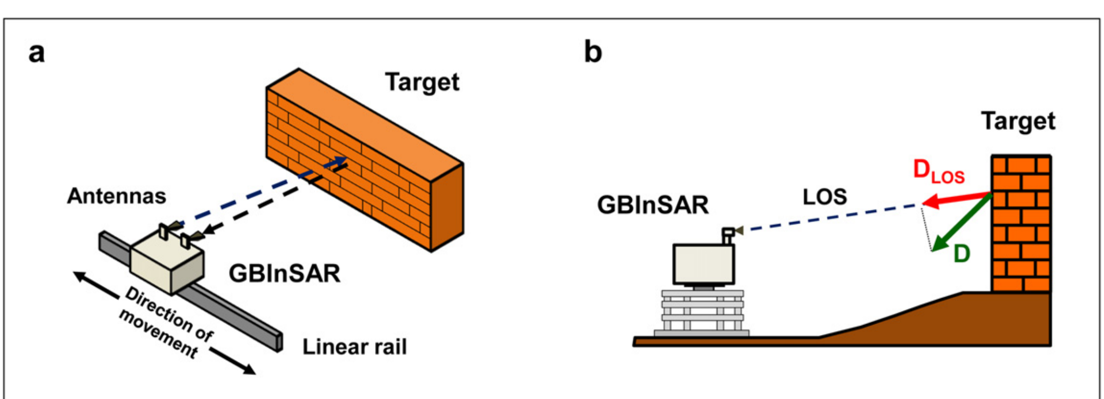

Fig. 1. Scheme of: a) SAR image acquisition by the GBInSAR, which collects the microwave signal backscattered by the irradiated object while moving along the linear rail; and b) measurement of the component along the Line Of Sight (LOS) of the sensor (D_{LOS}) of the real displacement vector (D) affecting the monitored object.

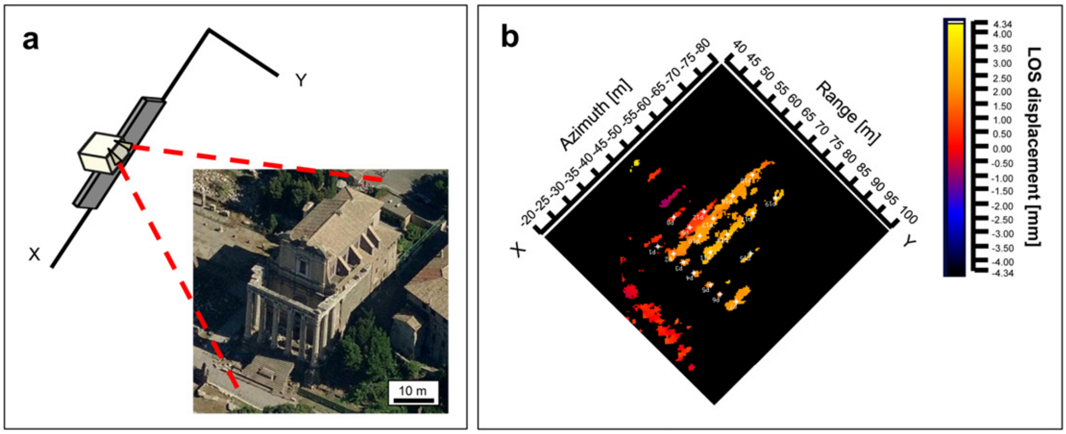

Fig. 2. a) The GBInSAR moves along the rail (*x* axis) to perform synthetic aperture radar and acquire a radar image of the interest monument. b) After range and azimuth synthesis of complex images and interferograms processing, LOS displacements are measured and visualized on 2D LOS displacement map.

As superficial technique, the GBInSAR only provides estimation of superficial deformation in correspondence to the surfaces it can clearly and continuously view. Nevertheless, the areal information distributed over a huge scene of observation offers an immediate and overall perception of the structural behaviour of the monitored surfaces. Use of a colour scale to represent the detected LOS displacements facilitates the comprehension for non-expert operators, allowing them to distinguish stable/unstable conditions and recognize clear deformation patterns (Fig. 2b).

The main outputs of data processing consist of: i) LOS displacement maps, and ii) deformation time series, i.e. graph of LOS displacements plotted vs. time. Data updating depends on sampling frequency, which can reach up to one SAR image every few minutes, i.e. the minimum time the radar sensor takes to complete the scan along the linear rail.

Such a high acquisition rate allows a real-time monitoring activity to be performed, with the possibility to detect faster deformation and displacements than those analysed by means of space-borne InSAR systems, such as ERS-1/2 and RADARSAT-1/2 satellites, which are characterized by roughly monthly repeat cycles (Cigna et al., 2011; Tapete et al., 2012, in press). The GBInSAR also can view areas shadowed or not perfectly observable from satellite radar sensors, such as steep slopes and north-facing surfaces (Casagli et al., 2010). Nevertheless, both the satellite and ground-based configurations of the InSAR technique can be integrated, especially to better understand the geometry and real value of the detected displacements. A demonstrative example of advantages/disadvantages of this integrated approach are illustrated in the discussion section based on the results from the validation tests of the GBInSAR data with satellite radar imagery processed by means of Permanent Scatterers algorithm (Ferretti et al., 2001).

Independently on the specificity of single model of radar instrumentation, the suitability of GBInSAR systems for structural monitoring have been recently investigated on historical buildings (Pieraccini et al., 2002), modern infrastructure (Tarchi et al., 1999) and bridges (Pieraccini et al., 2000). Although some authors have highlighted the loss of coherence (or decorrelation) for interferometric analyses over long time intervals, necessary to map very slow movements on the order of few centimetres per year (Zebker and Villasenor, 1992; Pieraccini et al., 2006), experiments of repeated measurements have confirmed the reliability of prolonged monitoring campaigns (Casagli et al., 2010; Luzi, 2010; Fanti et al., in press).

Besides the already mentioned limits of the GBInSAR technique (i.e. detection of displacements perpendicular to the LOS and decorrelation), further shortcoming is related to the two-dimensional visualization of the displacement data, according to the radar geometry. A top-down view does not allow sufficiently precise localization of the detected displacements and necessarily limits the reliability in identifying which architectural element is unstable. A possible solution proposed in this paper is the use of 3D data to achieve a perspectival view of the monitoring data over the observed scene.

2.2. Terrestrial laser scanning (TLS)

Non-invasiveness, acquisition over non-accessible areas at measurement distances up to hundreds of metres, high scan rate and accuracy of the survey up to few millimetres are well known properties of terrestrial long-range time-of-flight laser scanners. They are particularly suitable for surveying at architectural scale (English Heritage, 2007) in both natural and artificial contexts, with object/environment size up to kilometre (Böhler and Marbs, 2002). For each point of the scanned surface, the x–y–z Cartesian coordinates and the associated reflectance value are collected and stored within the point cloud reproducing the scene.

Generation of 3D models from point clouds usually includes a polygonal subdivision of the surface, using a triangle mesh to obtain a faithful description of the size and dimensions of the surface (Lerones et al., 2010). TLS 3D models are frequently used for purposes of 3D archaeological documentation (Al-kheder et al., 2009) and high resolution modelling and digital 3D imaging of structures (Arayici, 2007; Beraldin et al., 2000). Geometric information can be also used to analyse stability of rock cliffs (Abellán et al., 2006, 2011; Gigli and Casagli, 2011), and it is increasingly exploited to simulate rockfall hazard mechanisms and assess their impacts on historic sites (Fanti et al., 2012; Gigli et al., 2012).

Recent research have also confirmed the TLS suitability for deformation measurement (Monserrat and Crosetto, 2008) and structural monitoring (González-Aguilera et al., 2008; Park et al., 2007), although some operational drawbacks can arise. The main one is the time-consumption required by (semi-)automatic processing of the point clouds. Monitoring campaigns based on the comparison of high number of consecutive scans acquired at relatively high temporal frequency also face the issue of sustainable processing and management of large amounts of data.

According to the laser wavelength of the used TLS instrumentation, the different sessions of laser scanning are also to be carried out in good atmospheric conditions, with optimal illumination of the surface to scan, possibly reproducing similar conditions from one scan to each other and suitable to collect homogeneous optical images at different surveying times. Depending on the accuracy of the scans, the model accuracy might be sufficient for detection of no more than centimetre displacements, with underestimation of morphological changes of smaller magnitude.

In light of these potentials and limits, TLS was here selected to create 3D products to be used as geometric support during the monitoring activity. The highly detailed geometric representation of the scene of view was expected to improve the precision and feasibility of the spatial interpretation of the GBInSAR data.

2.3. Integration of GBInSAR and TLS

The rationale behind the proposed integration is to merge the TLS geometric information with the GBInSAR measures into a unique product, which enables operators to read detected LOS displacements directly on 3D representation of the observed scene and better localize the key areas of concern for the conservation of the monitored monument.

Previous published works which exploit the two techniques for monitoring purposes (Luzi et al., 2009; Pieraccini et al., 2006) have actually set up “combination methodologies”. They have exploited the following steps: 1) execution of separate GBInSAR and TLS measurement campaigns; 2) interpretation of their respective outputs; 3) final comparison and combination of the results to achieve better knowledge about the monitored phenomena.

Conversely, this paper proposes an “integration methodology” by merging the data provided respectively by the two techniques, to generate a new product where the LOS displacements are visualized on 3D geometry.

Such an integrated approach has been already tested for environmental/geological applications to monitor landslide phenomena in quarries and rock masses (Lingua et al., 2008; Mazzanti and Brunetti, 2010). In those cases, the issue of a correct georeferencing of the GBInSAR data on DEM/DTM produced from TLS point clouds was solved by means of targeted topographic tasks. A local coordinate system can be created measuring, by means of Total Station and/or GPS instrumentation, the position of control points and benchmarks distributed over the same scene observed by the radar and TLS.

Casagli et al. (2010) and Gigli et al. (2011) have clearly demonstrated the operational benefits of layering LOS displacement data directly on high resolution DEM, especially for scopes of early warning. The successful implementation of this approach on natural environments has encouraged its exportation to the field of built heritage preservation.

Besides the typology of the application context, the novelty of this paper consists in proposing GBInSAR – TLS integration supported by an automatic procedure to align the constantly acquired GBInSAR data with the TLS geometric support. This element is particularly relevant, because this improvement allows sensible reduction of time from the acquisition phase to the updating of the monitoring data, with benefits for early warning activities.

3. Radar monitoring of the Domus Tiberiana (Rome, Italy)

3.1. Geo-archaeological setting and conservation issues

The proposed methodology of GBInSAR – TLS integration was tested during the radar monitoring of the Domus Tiberiana in the historic centre of Rome, Italy. The monument was the former substructure of the Imperial Palace, built by the Romans in the first century AD at the top of the Palatino Hill (Fig. 3a). The remaining structures of the Domus Tiberiana still cover the northern and north-western sides of the hill, and they are formed by two distinct construction phases. The exterior part of them is constituted by series of arcades facing the Roman Forum, and corresponds to the enlargement erected by the Emperors Domitian and Hadrian along the Roman road called *Via Nova* (Fig. 3b).

Reasons for the structural instability which chronically affect the monument are to be found in the conservation history and local geohazard factors. Slow sliding of the masonries is thought to have started quite soon after the construction, since several deep cracks opened in ancient times (Martines et al., 2000). After the abandonment, the monument was filled for centuries, with soil up to about 30 m a.s.l., underneath the gardens of the palace built by the Farnese family. Archaeological excavations carried out between the nineteenth and twentieth centuries brought back to light the northern façade of the Domus Tiberiana, and new destabilization processes were triggered.

Archaeological Superintendence of Rome (2006) schematized the severe crack patterns visible on the masonry surfaces with decimetre-wide opening of the fissures. The latter structurally isolate the front of the building from the rear structures. Scarpelli et al. (1997) have also observed that the structures built before the enlargement and the part of the monument extending uphill from the *Clivus Victoriae* (the ancient road running behind the enlargement arcades) do not show such damages. This evidence seems to suggest that the structural issues mainly concern the exterior sector, with differential settlement as consequence of local ground instability.

A robust proof for this hypothesis was provided by the geological setting of the area. Along the perimeter of the Domus Tiberiana, particularly the northern flank of the hill, the volcanic cover constituted by superimposed tuff strata was eroded and filled by soft clayey silt, and the structures located towards the Via Nova are founded on these strata prone to slide (Fig. 3b). Also, the topographic survey carried out in 1985–1994 indicated a tendency of the part of the Domus Tiberiana facing the Roman Forum to move towards the north-east, with settlement rate of about 0.3–0.4 mm/yr (Scarpelli et al., 1997).

Several interventions were executed in the past decades, among which the insertion of systems of coupled stainless steel tie-bars with small diameter in the front façade and rebuilding of the ancient structures along the base to widen the buttresses (Carriero and Sabbadini, 2000; Fig. 3c). Nevertheless, geodetic measurements have registered displacements until 2009, with a significant acceleration in January 2007–April 2008 and velocity up to 3.5 mm/yr (Ascoli Marchetti, 2009). Confirmation was also retrieved from the satellite monitoring campaign performed by processing radar imagery acquired by the ERS-1/2 satellites for the period April 1992–December 2000 with Permanent Scatterers technique (Ferretti et al., 2001), whose results were recently published by Tapete et al. (2012).

In light of these persistent conservation issues, a “single monument scale” monitoring by means of the GBInSAR Lisamobile was activated in April 2009 and coupled to a targeted TLS survey, to detect structural deformation of the Domus Tiberiana throughout one year of acquisition, until March 2010.

3.2. Integrated radar monitoring

The workflow of the integrated methodology tested on the case study of the Domus Tiberiana includes the following three main phases: 1) on site installation of the radar instrumentation and acquisition of displacement data; 2) TLS survey and production of point clouds and 3D models; 3) integration of the GBInSAR data and

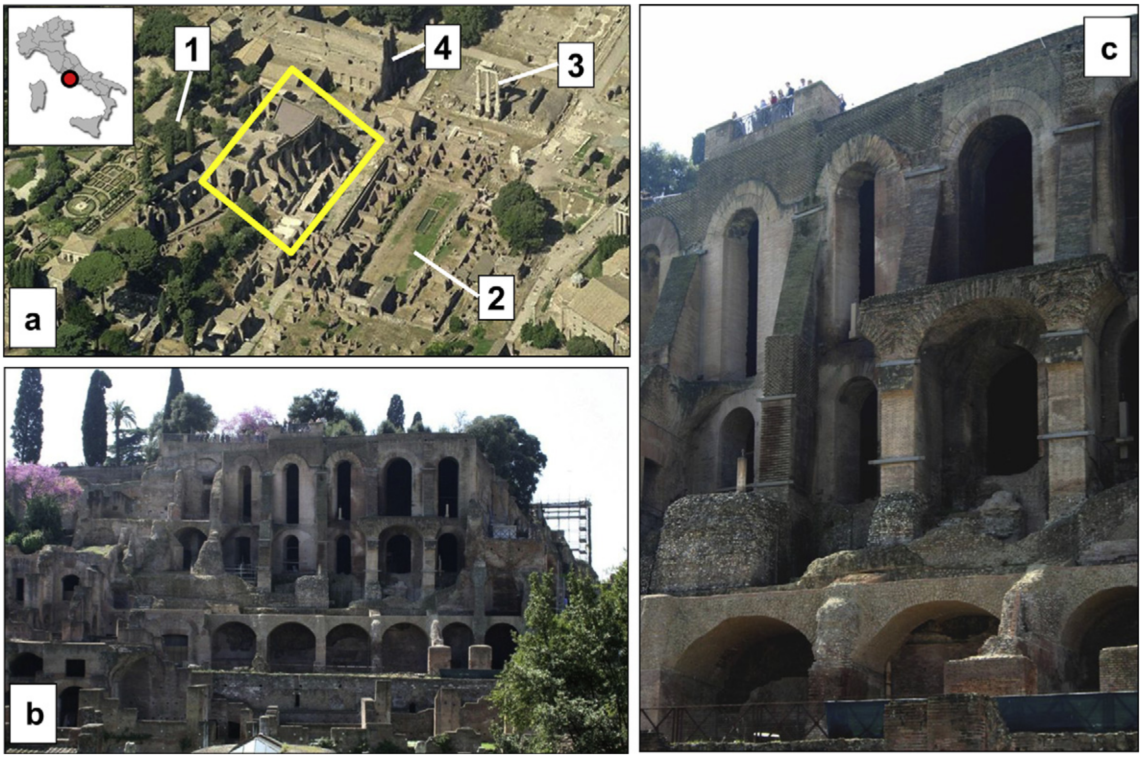

Fig. 3. a) Aerial view of the Roman Forum with: 1) the northern sector of Palatino Hill, 2) the House of the Vestal Virgins; 3) the Temple of Castor and Pollux and 3) the Aula Domizianea. b) View of the substructure arcades of the enlargement of the Domus Tiberiana towards the Roman Forum (yellow square in picture a); c) with detail of the historical interventions on the arcades pillars executed to contrast the structural instability of the monument, and the recent reconstruction works along the Via Nova. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

TLS point cloud to obtain the so-called "3D interferometric radar point cloud" as final product.

3.2.1. On site installation and radar data acquisition

The GBInSAR Lisamobile instrumentation used in the tests is property of the University of Firenze and was purposely adjusted by the ellegi srl – LiSALab company. The transceiver unit is based on a continuous-wave step frequency radar with central frequency of 17.3 GHz, and it moves along a linear rail of around 1.5 m of length, thereby generating 1.5 m-wide synthetic aperture. The corresponding wavelength leads us to obtain sub-millimetre sensitivity in the estimation of LOS displacements. In the simplest case when main artefacts and ambiguities introduced by the real measurements are negligible, a linear relationship links the

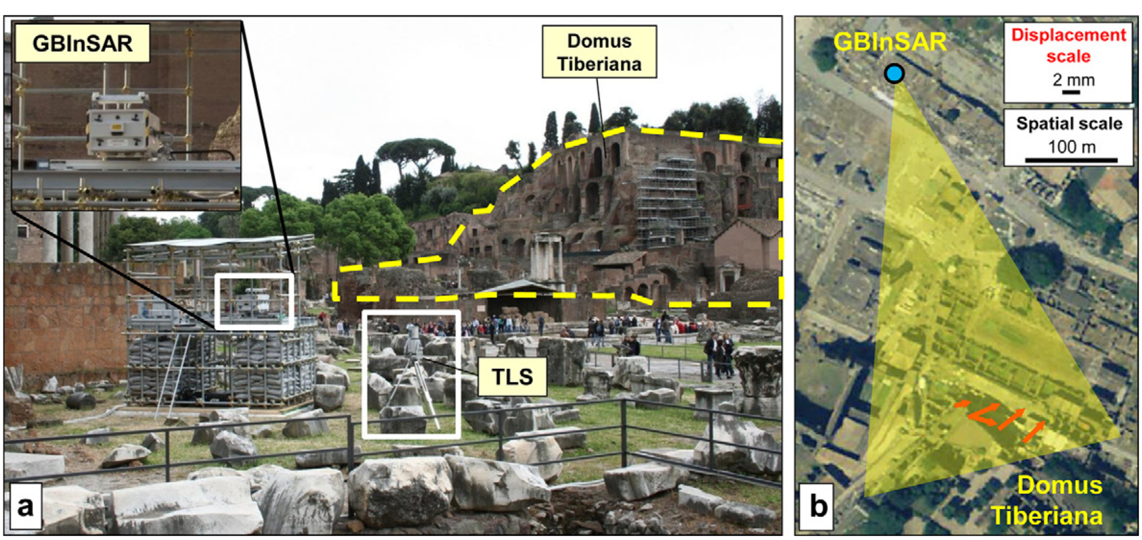

Fig. 4. a) The GBInSAR Lisamobile, mounted on stable scaffoldings, with view centred on the Domus Tiberiana (dashed yellow line), while carrying out the TLS survey. b) The installation site assured an effective acquisition geometry, adjusting the field of view (yellow cone) also considering the directions of movements hypothesized based on the 1985–94 cumulated horizontal displacements (red arrows) published by Scarpelli et al. (1997). The displacement scale is referred to the length of the red arrows to clarify their respective magnitude. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interferometric phase to the occurred LOS displacement (Rosen et al., 2000).

The area covered by the GBInSAR Lisamobile roughly corresponds to an angular sector of 57°, and the view was optimized by rotating the antennas to cover most of the monument of interest. Nevertheless, shadowed areas were not completely avoided in the interferograms, since the archaeological remains of the Roman Forum facing the Domus Tiberiana created physical obstacles to achieve a 100% coverage of the external surfaces of the monument.

Anyway, the installation site offered the following conditions: a fixed and stable position to guarantee the zero baseline geometry; a sufficiently clear view of the monuments to monitor; radar-target distances of about few hundreds of metres, necessary to retrieve an acceptable azimuth resolution for the different planes of observation (spanning from 0.1 m at 10 m–1.8 m at 310 m).

The review of previous studies and monitoring campaigns were essential to have a preliminary idea, as much precise as possible, about the past/recent structural issues of the monuments, to address the setting up of the radar acquisition geometry. In absence of any information, specific engineering evaluation is usually recommended to hypothesize which typologies of structural destabilization processes are affecting the monument.

In the present case, stable scaffoldings were erected in front of the Basilica Aemilia, facing the northern and north-western sides of Palatino Hill, and the GBInSAR Lisamobile view was centred in correspondence to the Domus Tiberiana (Fig. 4a). Thanks to the installation within a restricted area, the monitoring campaign was carried out without interruptions or restrictions of the public opening of the archaeological site of the Roman Forum. Safety for visitors and protection from possible interference for the radar measuring were consequently guaranteed.

The GBInSAR Lisamobile acquisition geometry was set up also taking into account the expected major directions of displacement, as mainly deduced by the already mentioned topographic survey carried out in the period 1985–1994 (Scarpelli et al., 1997). Based on both historical data and the more recent structural stability assessment (Archaeological Superintendence of Rome, 2006), the GBInSAR Lisamobile view direction was set not perpendicular to the expected major direction of the deformation movements (Fig. 4b). This was thought to increase the probability of better estimation of D_{LOS} for most of the points of the scene. Indeed, angles between the LOS and the major direction of displacements approaching 90° bring to high underestimation, even zero-measure set, of D_{LOS}.

To guarantee a stable positioning, the scaffoldings were founded onto a planar sand-filled basement suitable to avoid displacements during the monitoring campaign, due to local micro-seismic activity, terrain shrinkage/swelling cycles and thermal contraction/expansion cycles of the metallic materials as response to the outdoor exposure. The latter were carefully taken into account during the mounting of the linear rail onto the scaffoldings, to prevent the occurrence of any displacement that could create an error interfering with the LOS displacement measures.

No rapid displacements were expected to be found during the monitoring. Jointly with the local conservators, the sampling frequency was set up one SAR image every 6 min. Hence, the structural behaviour of the Domus Tiberiana was continuously monitored, associated to a quasi real-time configuration in relation to data processing. Further advantage was obtained by the use of an automatic procedure for production of the LOS displacement maps and related deformation time series.

Focusing algorithm provided SAR images as two dimensional maps and the attained resolution grid size shown in Fig. 5 is strictly dependent on the selected technical parameters summarized in Table 1.

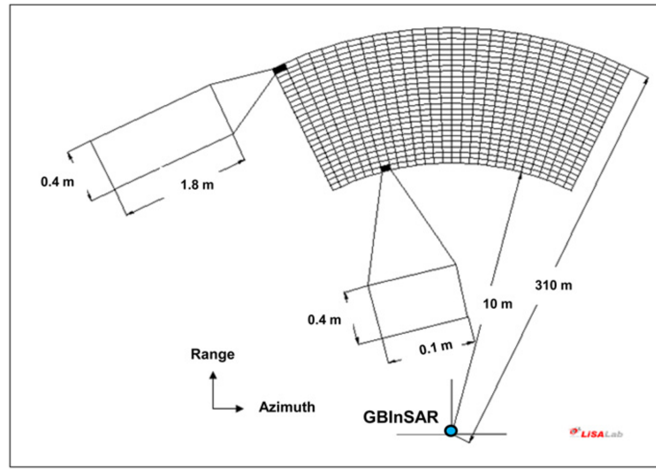

Fig. 5. Resolution grid size achieved during the integrated radar monitoring of the Domus Tiberiana.

The interferogram obtained by comparing two or more SAR images acquired from the same position is a map with the same spatial features of the SAR images and whose phase variation, namely the "interferometric phase", can be linearly related to the LOS displacement occurred on the observed surface during the elapsed time. A positive value means an increase of the sensor-target distance, while negative values refer to a decrease of this distance.

As the measured phase can assume only values within $-\pi$ and $+\pi$ (a finite interval), phase values measured in presence of displacements larger than $\pm$ half-wavelength are ambiguous (wrapped). This fact results in an interferogram with the typical fringe pattern. The procedure to "unwrap" the measured value can be applied if the noise of the interferogram is low. The wrapping for the GBInSAR Lisamobile occurs for displacement greater than 0.8 cm, which is a value largely far from those expected for the Domus Tiberiana. It implies that this type of issue was of minor concern for the present case.

To retrieve the temporal evolution of the monitored area, interferograms can be obtained following two different approaches: i) by comparing pairs of images acquired at different times separated by same interval (rolling method), or ii) taking an image as a reference and one acquired at different increasing time (incremental method). In the latter case, wrapping is highly probable and a different representation scale has to be adopted.

Concerning the atmospheric artefacts which can affect radar interferometric data and possible solutions to remove it (Zebker and Villasenor, 1992), it is generally probable that the interferometric phase may contain a spatially and temporal variable term related to atmospheric parameters variation, increasing with the

Table 1
The GBInSAR Lisamobile parameters set up for the radar monitoring of the Domus Tiberiana.

Polarization	VV
Central frequency	17.3 GHz
Bandwidth	400 MHz
Length of synthetic aperture	1.5 m
Minimum sensor-target distance	10 m
Maximum sensor-target distance	310 m
Range resolution	0.4 m
Azimuth resolution at 10 m	0.1 m
Azimuth resolution at 310 m	1.8 m
Measurement time	6 min

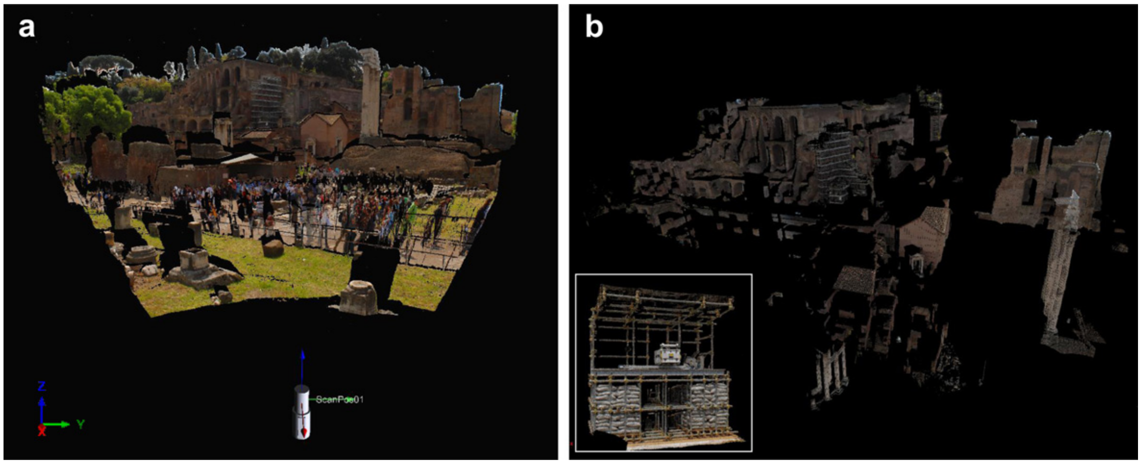

Fig. 6. a) Point cloud, textured with the optical image, taken from the scan position reproducing the view of the GBInSAR instrumentation; b) final holistic 3D point cloud of the Domus Tiberiana and the surrounding monuments of the Roman Forum, including also the geometry and position of the GBInSAR LisaMobile and its rail (inset), exploited as geometric support for the radar monitoring. Note the presence of restoration scaffoldings at the corner of the Domus Tiberiana at the time of the radar monitoring.

distance between the radar and the observed area. Due to the short range (up to 310 m) reached with the set up established for the radar monitoring of the Domus Tiberiana and thanks to the high rate of available measurements, this problem resulted of minor concern and was overcome.

3.2.2. Point cloud acquisition

During the radar installation, a session of TLS scans was performed to acquire the 3D geometry of the Domus Tiberiana and the surrounding monuments of the Roman Forum. The survey was undertaken using a Long Range and High Accuracy time of flight TLS system RIEGL LMS-Z420i (Riegl, 2010a), and the associated operating and processing RiSCAN PRO software package (Riegl, 2010b). Point clouds can be acquired at a measurement range up to 1000 m, against 80% of target reflectivity, exploiting angular resolution up to 0.002° and 0.004°, respectively, for vertical (line) and horizontal (frame) scanning.

For a best integration with the GBInSAR data, the TLS survey included scans collected from different positions distributed over the area of interest, useful to retrieve an overall point cloud reducing shadow areas. The first scan was acquired from a scan position very close to the installation site of the GBInSAR Lisamobile, to collect a point cloud with the same viewpoint as the radar (Figs. 4a, 6a). This scan constituted the main geometric reservoir to generate the 3D point cloud to support the spatial interpretation of the GBInSAR data.

Several cylindrical reflectors were distributed over the area to be scanned as tie points clearly visible from all the scan positions. They were useful in the subsequent phase of scans registration ("cloud alignment") to guarantee a sufficient overlapping between adjacent TLS point clouds while merging them into a unique holistic point cloud. A Leica 1200 Differential Global Positioning System (DGPS; Leica Geosystems, 2009) was employed to retrieve the coordinates of the cylindrical reflectors distributed as tie points over the Roman Forum and above the structures of the Domus Tiberiana, adopting a Real-Time Kinematic (RTK) procedure. As summarized by Sturzenegger and Stead (2009), different approaches, varying in relation with time and costs of the survey, can be used to register 3D point clouds. The RTK method provides an easy-to-use and smart procedure, against its centimetre

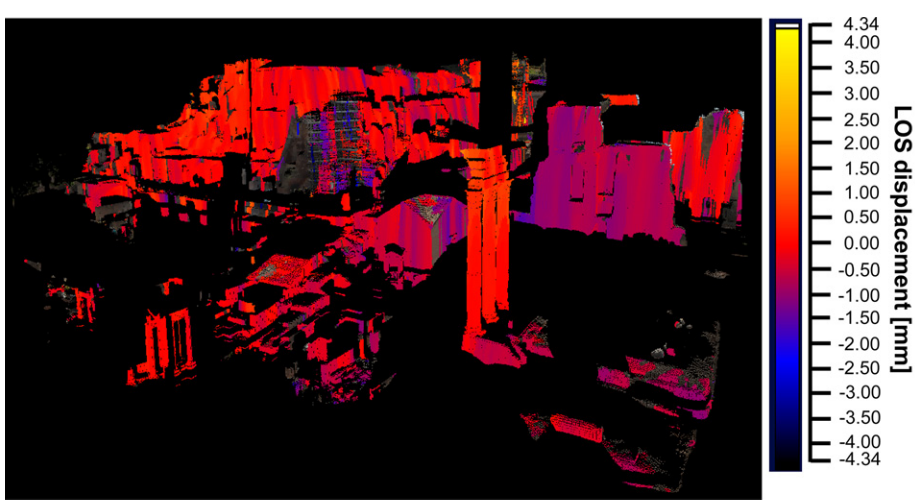

Fig. 7. 3D interferometric radar point cloud of the Domus Tiberiana and the surrounding monuments of the Roman Forum showing cumulative LOS displacements measured in the period 18 April – 3 June 2009. The blue-violet colours in correspondence to the restoration scaffoldings (compare with Figs. 4 and 6) is an artefact due to the disturbance created by the metallic materials of the scaffoldings themselves and the ongoing restoration activities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

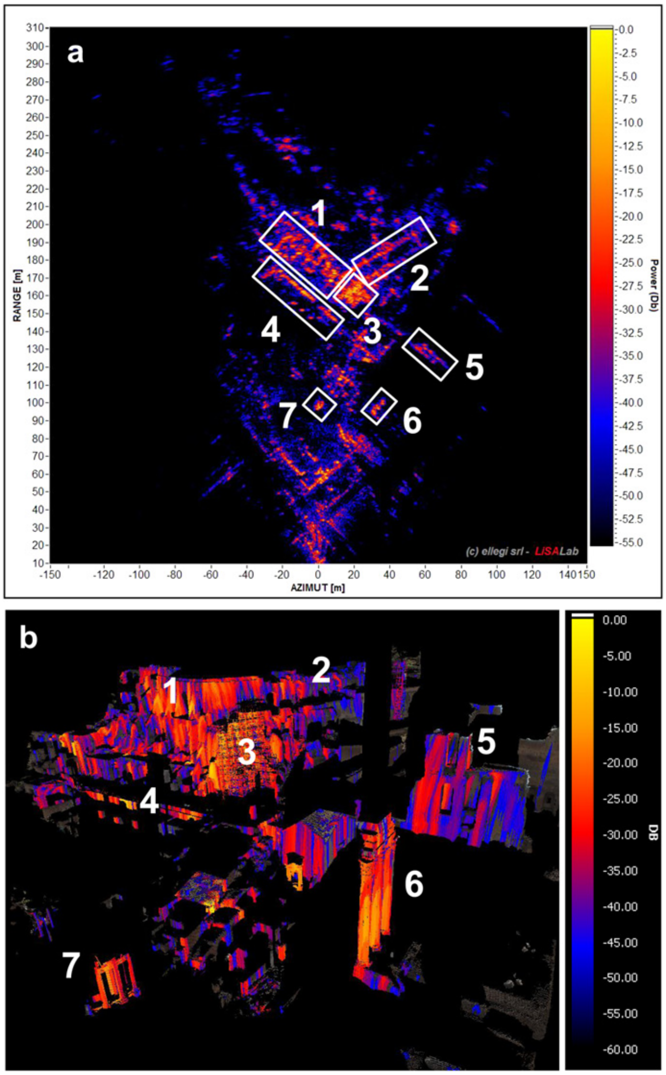

Fig. 8. Recognition of the monitored monuments using the power image in: a) 2D visualization according to the radar geometry; and b) 3D visualization exploiting 3D interferometric radar point cloud. The corresponding numbers are referred to: 1) substructure arcades and 2) north-western sector of the Domus Tiberiana; 3) restoration scaffoldings; 4) House of the Vestal Virgins; 5) the Aula Domizianea; 6) Temple of Castor and Pollux; 7) Temple of Vesta.

accuracy, to create a sufficiently dense GPS network as a common reference frame for TLS point clouds.

Before meshing the merged 3D point cloud, the raw data were filtered removing gross errors, isolated points and all the information not pertinent to the monuments. During this preprocessing stage, the removal of the vegetation is necessary to reduce the noise in point clouds that might affect the subsequent phases (Buckley et al., 2008).

The following step is data triangulation to retrieve a 3D triangular mesh, which leads to generate a congruent surface of the sampled/decimated point cloud, with correct orientation of the triangle normals. The 3D model reproducing the Domus Tiberiana and the other monuments of the Roman Forum has required a total number of 335,000 polygons.

The exact position and orientation of both the radar instrumentation and its rail were also collected, to correctly align the displacement data acquired by the GBInSAR Lisamobile on the TLS point cloud. This further justifies the execution of first TLS scans from a scan position close to the GBInSAR Lisamobile installation site, which include the radar instrumentation itself and its equipment (Fig. 6b).

3.2.3. 3D interferometric radar point cloud

The final output of all the above described workflow is the “3D interferometric radar point cloud” (Fig. 7). This product merges the displacement information with the geometric ones, keeping all the peculiarities of the integrated radar and laser-based techniques.

The high spatial resolution and the true 3D character are therefore assured by the real colour high resolution point cloud of the area of interest obtained from the TLS survey. In the present case, the holistic point cloud was constituted by more than 2.1 million of points.

The choice of the point cloud, instead of the derived polygonal surface, to create the final integrated output (Fig. 7) is supported by the need to keep as much of the original information as possible, thereby limiting geometrical simplifications which inevitably affect the meshing phase. The latter, especially in case of irregular geometric scenes like the investigated one, often causes the loss of details of specific interest.

The point cloud is georeferenced according to a local reference system, and each point is associated to its x–y–z coordinates and the RGB values, the latter extracted from the digital images acquired by the camera mounted over the laser scanner.

As already stated, one of the scan positions was located near the GBInSAR Lisamobile site, with the dual objective to obtain a similar view which could facilitate the alignment phase, and to exactly locate on the point cloud the position and orientation of the radar instrumentation and the rail along which it moves (Fig. 6b).

The precise knowledge of the radar position addresses the georeferencing phase of the point cloud on the GBInSAR data. This operation is performed once, during the first alignment iteration. At this stage, we use the power image, i.e. the image related to the amplitude of the backscattered signal collected by the GBInSAR Lisamobile (Fig. 8a), because it usually allows a clear distinction of the different elements within the observed scene, based on the amplitude of the backscattered GBInSAR signal. Comparing the power image and the high resolution point cloud, common elements visible in both of them were matched, to establish a fixed and strong spatial association between the radar signal recorded in the interferograms and the corresponding real elements reproduced on the 3D. This georeferencing phase is still valid, until significant changes occur within the scene of view. In such a case, the TLS survey is to be renewed by executing a further scanning campaign.

The resulting roto-translation parameters are subsequently put within an automatic procedure, which is updated whenever new interferograms are produced. In this way it is possible to obtain a new 3D reference system with the x and y axes, respectively, parallel and perpendicular to the GBInSAR Lisamobile rail direction, and z axis normal to the x–y plane. Hence, the observed scene is finally viewed as if observed by the GBInSAR Lisamobile from its installation position.

To each point of the cloud, the radar processing software associates the intensity of the reflected signal and the phase information, allowing LOS displacements to be retrieved. This procedure is completely automatic and the data processing routines have been optimized to speed up the computing phase, and save hardware resources, with particular attention to the RAM resource. Such an automatic updating system permits immediate accessibility to x–y–z coordinates and RGB information for each sector of interest, highly suitable to perform real-time monitoring and early warning of sudden displacements and anomalies deviating from expected trends.

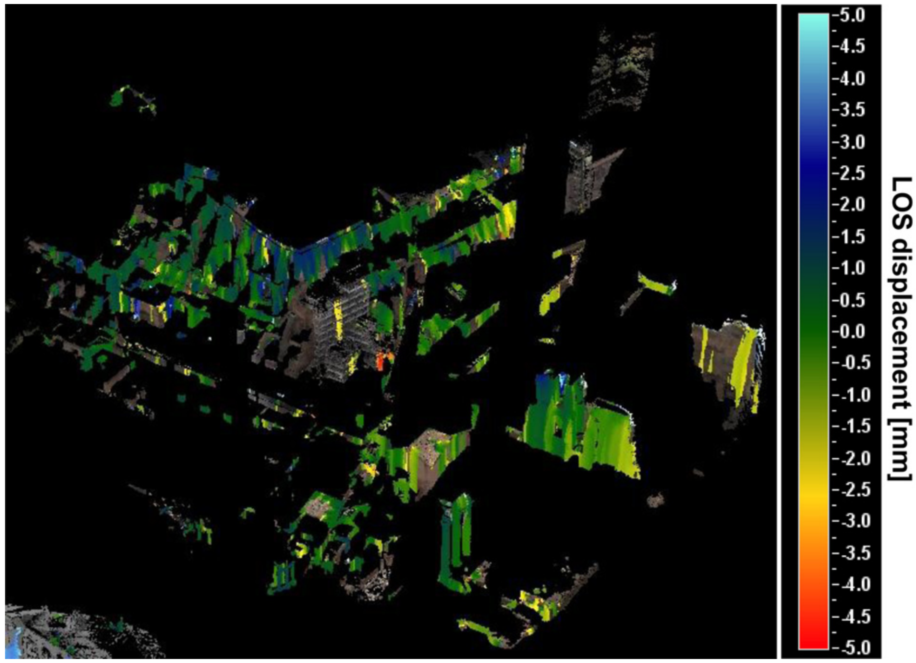

Fig. 9. 3D interferometric radar point cloud with the cumulative LOS displacements measured at the end of the monitoring period (April 2009–March 2010).

4. Results and discussion

4.1. Radar-interpretation for structural monitoring

The first step of the radar monitoring was the recognition of the archaeological structures within the LOS displacement maps. The commonly used procedure consists of the analysis of the power image of the observed scene. The comparison with photographs of the monuments taken from the radar position allowed all the sectors viewed by the GBInSAR Lisamobile to be zoned with acceptable level of reliability (Fig. 8a). The elements which guide this phase are the amplitude of the backscattered GBInSAR signals and their shape. The northern and north-western sectors of the Domus Tiberiana were totally covered, as well as the columns of the Temple of Castor and Pollux, the Temple of Vesta, the House of the Vestal Virgins and the Aula Domizianea (compare with Fig. 3a).

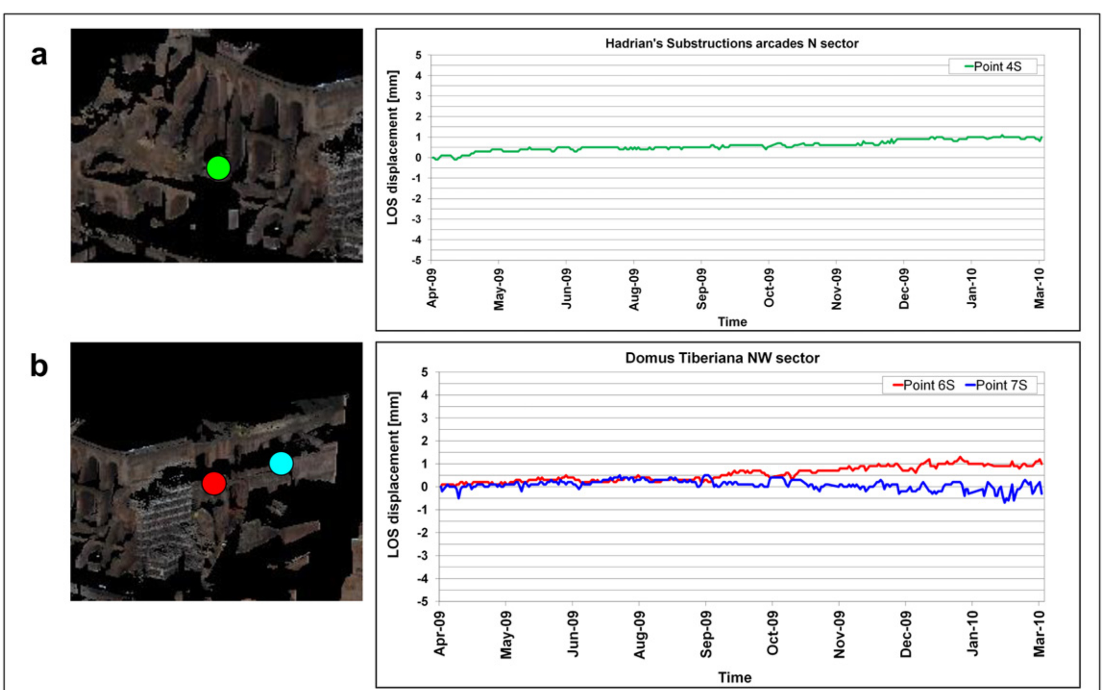

Fig. 10. Time series of control points which exemplify: a) absence of cumulative LOS displacements; and b) condition of “relative stability”, with cumulative LOS displacements not exceeding the stability threshold.

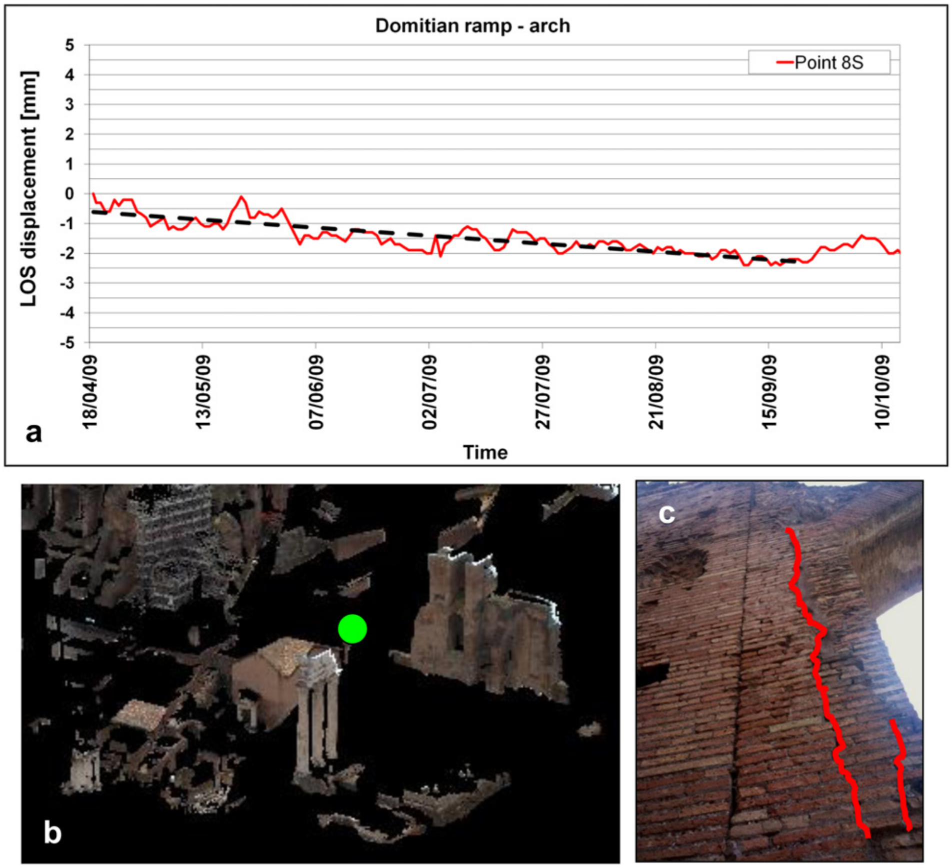

Fig. 11. a) Time series recorded for the point 8S, localized in correspondence to the walls of an arch connecting two masonries in front of the Domitian ramp (b), which clearly shows a constant displacement trend towards the sensor in the period April–September 2009. c) An extended crack pattern (red lines) affects the masonry of the supporting pillars of the arch. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nevertheless, the 2D visualization was not sufficient to provide the required detail in localizing the monitored areas. A significant improvement was derived thanks to the integration between the power image information and the 3D model. The archaeological structures are immediately recognizable also for non-expert investigators (Fig. 8b). As expected, the areas shadowed for the GBInSAR Lisamobile were empty, while elements with high reflectivity showed high signal in the power image, such as the scaffoldings located at the corner of the Domus Tiberiana (area 3 in Fig. 8).

Before selecting the control points useful to assess the stability of the monuments, the structural behaviour of the monitored surfaces was preliminarily evaluated. In this way, a “stability threshold” was defined to have a reference to assess if a detected LOS displacement is to be considered relevant, or even alerting. The thresholds concerned both the daily and the cumulative values of LOS displacements, and they were established based on the GBInSAR measurements performed in the first two months of the monitoring campaign (April–June 2009). In particular, we analysed LOS displacement maps obtained from the interferograms processed by means of rolling and incremental methods.

Cumulative LOS displacement maps averaged at 24 h and processed with rolling method, i.e. considering an elapsed time between them of about 9 days, confirmed the absence of deformation higher than ± 0.5 mm measured along the LOS within the observed scene. Consequently, the range of ± 0.5 mm per day was set as the daily stability threshold for the present monitoring. Hence, displacements with values within the threshold were not considered as real displacements. This assumption was directly validated based on direct on site evaluations carried out by the Archaeological Superintendence of Rome and thanks to the experience of the local conservators on thermal contraction/expansion behaviour of the ancient structures. This on site control was essential to distinguish thermal effects due to sun radiation over the monitored surfaces and seasonal temperature changes.

The radar-interpretation of cumulative LOS displacement maps averaged at 24 h and processed with incremental method, i.e. applying a constant increase of about 9 days, showed the absence of deformation appreciable along the LOS in correspondence to the substructure arcades and the north-western sector of the Domus Tiberiana, while some displacement anomalies were localized in the Aula Domizianea and in the Temple of Castor and Pollux (Fig. 7). The threshold for cumulative LOS displacements was finally fixed at the range of ± 1.0 mm.

In particular, LOS displacements exceeding this threshold were considered alarming, if they persistently deviated from the stability trend and configured a definite trend away from or towards the sensor (with, respectively, positive and negative values of LOS displacements and related LOS deformation rates).

The two main criteria of the established early warning procedure to send an alert were: 1) the occurrence of cumulative LOS displacements exceeding the threshold, and 2) the presence of a clear displacement trend suggesting further evolution into serious (reversible or irreversible) deformation for the monitored structure.

At this stage several areas showing homogenous values of cumulative LOS displacements were recognized (Fig. 7). Control points were purposely selected over these areas to be representative of their structural behaviour. So, monitoring the displacement

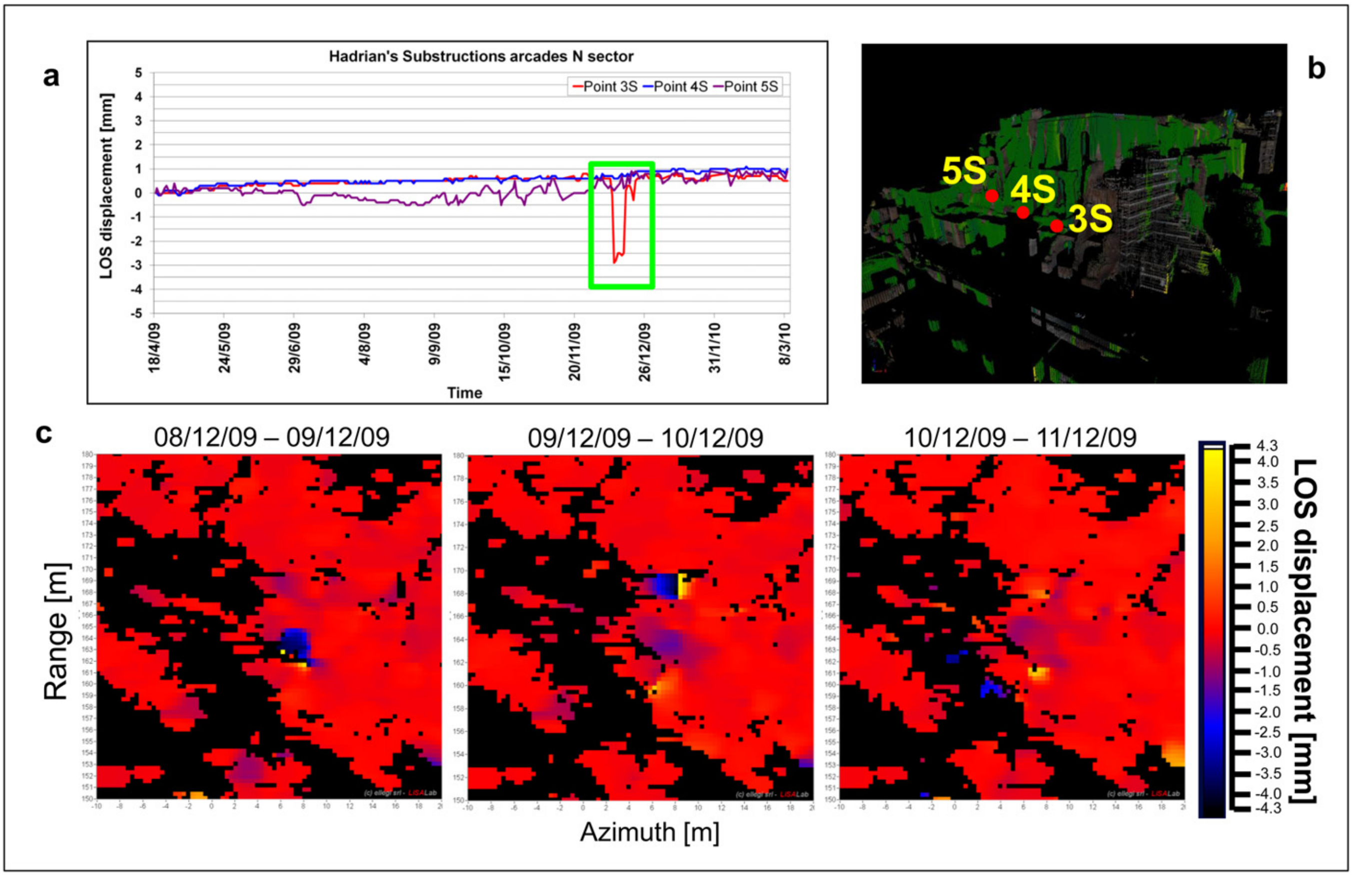

Fig. 12. a) Time series analysis for three points selected in correspondence to the lower arcades of the Domus Tiberiana (b) showed sudden displacements for the point 3S in December 2009. c) Clear deformation pattern with LOS displacements towards the sensor was identified in the LOS displacement maps and it was constantly monitored during the entire warning phase (8–12 December 2009). Each LOS displacement map is referred to a time interval of 24 h.

trends of the time series of these points was a sustainable method to continuously monitor the evolution and/or stability of the displacement trends characterizing all the related sectors.

Throughout the whole monitoring period (April 2009–March 2010), no permanent deformation patterns were highlighted over the structures of the Domus Tiberiana and the surrounding monuments of the Roman Forum. Fig. 9 displays the cumulative LOS displacements estimated over almost one year of monitoring. The measured LOS displacements only occasionally reached values higher than the threshold, but never exceeding the maximum values of $+2.5$ mm away from the sensor and -2.5 mm towards the sensor. The trends tended to an overall stability, with alternation of displacement phases with opposite directions of movement.

With specific regard to the substructure arcades of the Domus Tiberiana, the monitoring campaign revealed a condition of quite relative stability. No relevant components of real displacement vectors were measured along the LOS of the radar sensor. It allowed us to exclude the occurrence of deformation along this direction and give the local conservators a reliable proof of the stabilization effect induced by the recent restoration works carried out by the Archaeological Superintendence, with the reconstruction of the lost/damaged architectural elements of the arcades along the Via Nova (Fig. 3c).

This result was highly significant in the perspective of planning near future interventions, since it was also validated by the results achieved from the satellite radar monitoring performed in 2009 (Tapete et al., 2012), exploiting RADARSAT-1 ascending data stack processed with Permanent Scatterers algorithm (Ferretti et al., 2001).

4.2. Spatial and temporal analysis for surveillance purposes

Detailed analysis of the deformation time series constantly retrieved for the selected control points showed different situations over the monitored monuments, particularly if they are observed with regard to short temporal intervals. The displacement trends found during the monitoring can be classified as follows: (i) absence of cumulative LOS displacements (Fig. 10a); (ii) "relative stability", with cumulative LOS displacement values within the stability threshold (Fig. 11b); (iii) LOS displacements showing a clear deformation trend (Fig. 11). To correctly classify each displacement trend, both the magnitude of the measured cumulative LOS displacements and their tendency to develop into deformation were considered.

In particular, the occurrence of the third structural situation is crucial to preventively detect conservation issues on monuments. The recognition of a progressive trend allows a specific warning to be activated. The alert procedure consisted in giving the local conservators both the precise location of the area to be inspected and a rapid analysis of the suspicious displacements to be verified on site.

A highly demonstrative example of the capability of the GBInSAR – TLS integration for early warning was offered by the LOS displacements measured for the walls of an arch connecting two masonry structures close to the Domitian Ramp, in front of the

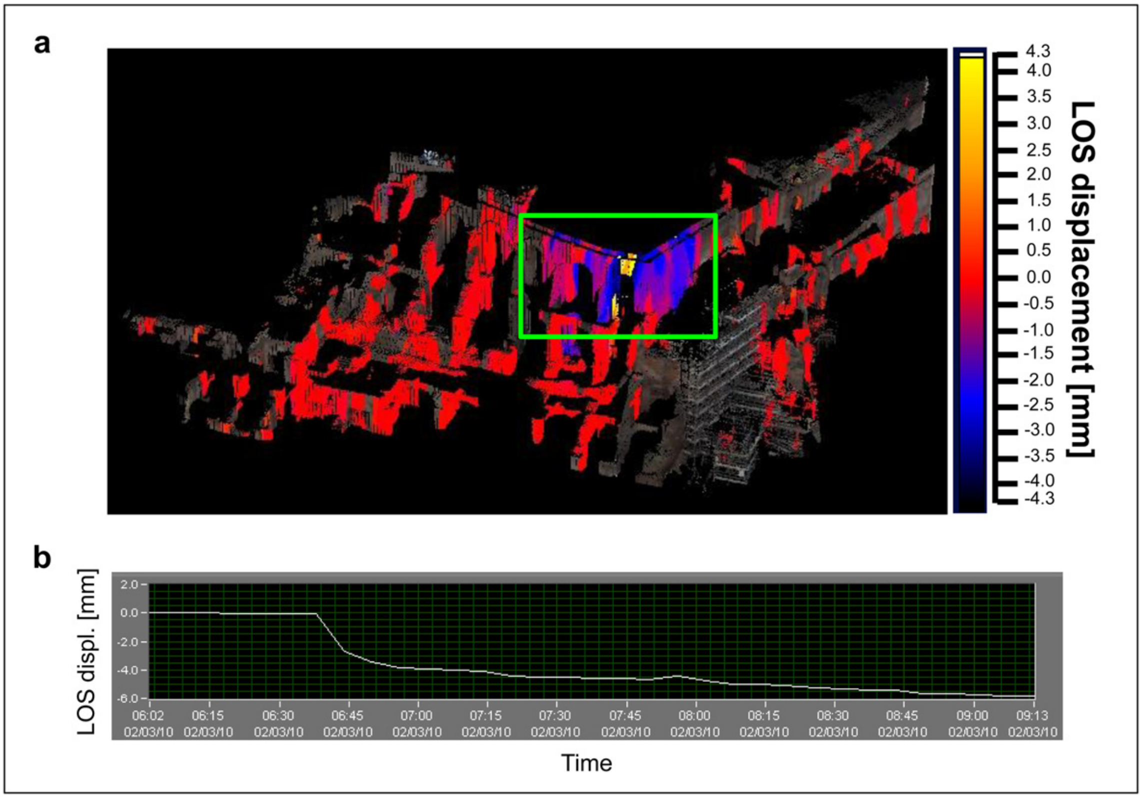

Fig. 13. a) Deformation pattern localized in the area of the Domus Tiberiana affected by the effects due to borehole investigations; b) related deformation time series with sudden displacement as significant deviation from the previous stable trend.

north-western side of the Palatino Hill (Fig. 11a–b). The time series showed clear trend, with constant movements towards the GBInSAR Lisamobile position measured over five months (April–September 2009) up to about −2.5 mm (Fig. 11a). The persistent tendency to move towards the sensor and the restricted area affected by the displacements were considered sufficient to warn the local conservators, to execute prompt on site inspections. Huge cracks were found over the masonry of the two pillars supporting the arch (Fig. 11c), and it suggested a potential correlation between a recent (re-)opening of the cracks and the detected LOS displacements. The direct consequence of such a point-wise warning was the updating of the condition report for the masonries of the arch, highlighting the need to plan urgent provisional interventions, awaiting a complete consolidation of the entire structure.

The effectiveness of this surveillance activity was demonstrated for a wide spectrum of events, included human activities, such as restoration works and on site diagnostic investigations.

The selectivity of the integrated approach to distinguish different structural behaviour between neighbouring areas was confirmed during the event occurred on December 2009 (Fig. 12). One of the three control points (point 3S) selected in correspondence to the homogeneous areas identified over the lower arcades of the Domus Tiberiana started to abruptly change its displacement trend, with sudden movements initially thought to be correlated to potential instability (Fig. 12a–b). The comparison with the time series of the other two points (points 4S and 5S) emphasized the suddenness of the LOS displacements observed for the point 3S and encouraged to activate the warning procedure.

A clear deformation pattern with increasing values of cumulative LOS displacements towards the sensor was identified over the area represented by the point 3S. LOS displacements maps (Fig. 12c) and related deformation time series were continuously monitored. The analysis of the displacement trend highlighted the following sequence of mean values of LOS displacements:

- 0.01 ± 0.05 mm between 00:03 and 23:58 on Tuesday 8 December;
- −0.04 ± 0.12 mm between 00:03 and 13:06 followed by −2.79 ± 0.17 mm between 13:18 and 23:58 on Wednesday 9;
- −0.05 ± 0.23 mm over the whole day, on Thursday 10;
- −0.05 ± 0.09 mm between 00:05 and 9:33 followed by 1.60 ± 0.18 mm between 9:39 and 12:08, and it finally became definitely stable again around 13:00 on Friday 11 with 0.32 ± 0.08 mm.

As already perceived from this sequence and further confirmed after on site inspections, the detected LOS displacements were finally found as anomalies rather than real displacements. They were actually caused by the operations necessary to install permanent metallic shoring and scaffoldings underneath the arcades, preparatory to the upcoming restoration works.

Further benefit of the GBInSAR – TLS integration for ordinary monitoring activities was highlighted with the detection of deformation as effects of invasive investigations. On March 2010 the execution of boreholes in the brick masonry of the façade of the Domus Tiberiana produced a definite and localized deformation pattern in the interferogram (Fig. 13a), coupled with sudden displacements recognized within the quasi real-time deformation time series of the control points selected in the area perceived as unstable (Fig. 13b). The concentrated deformation pattern exactly marked the sector affected by the effects of the boreholes on the masonry, against the surrounding area completely stable, without relevant displacements detected along the LOS of the GBInSAR

Lisamobile. Also for this case, the direct positioning on the 3D interferometric radar point cloud led to a certain identification of the sector affected by the displacements, thereby confirming the corresponding deformation pattern observed in the planimetric view of the interferogram according to the radar geometry.

4.3. Implications for conservation

The direct impact on the conservation strategy adopted by the Archaeological Superintendence consisted in having clarified that no significant displacement trends were developed along the LOS of the radar during the monitoring period. It allowed this direction to be excluded as the main direction of the deformation having presumably affected the structures of the Domus Tiberiana.

The condition of relative stability found in correspondence to the substructure arcades was interpreted as an indirect proof of the appropriateness of the recent restoration works executed at the base of the archaeological complex, along the Via Nova. It also suggested the need to continue consolidation works to stabilize the archaeological structures, repair the cracks over the masonries, and remove the brick-concrete vaulting of the arcades dated back to the 1960–70s. The outcomes of the integrated radar monitoring also contributed to update the condition report of the Domus Tiberiana.

The high precision of the 3D interferometric radar point cloud to indicate the location of the detected displacements and the high frequency of SAR images acquisition are undoubtedly to be mentioned among the remarkable advantages of the GBInSAR – TLS integration. Quasi real-time analysis of the displacement field of entire monuments might become a new tool for the routine surveillance in archaeological sites, especially considering that the portability of the GBInSAR Lisamobile allows both long term and temporary monitoring campaigns to be carried out. According to the specific analytical needs, the acquisition can be initially focused on a portion of the studied monument and, afterwards, moved to another sector.

Nevertheless, the improvement with TLS data does not solve the issues related to shadowed areas and interference due to alteration of the observed scene. The findings obtained during the event occurred on December 2009 testify the limits of this remote sensing-based approach. Anomalies can be easily misinterpreted, with consequent hazard of sending false alarms. A possible solution might be the installation of a camera close to the radar to have a constant view of the observed scene. Similarly, an infrared camera can solve the problem during night.

Despite these limitations, the GBInSAR – TLS integration make the interaction between the displacement detection phase and the execution of on site inspections more feasible and easy-to-perform. Benefits can also raise for the setting up of shared monitoring and early warning procedures, which directly involve the local conservators.

The immediate identification of ongoing/upcoming structural instability and the direct communication/validation process can effectively support the local conservators in decision-making, providing them with the necessary knowledge to undertake provisional measures to temporarily stabilize the structure till the execution of final consolidation works, and even close the area affected by instability to the public opening until the safety conditions are properly ensured.

5. Conclusions

The integration of the deformation data derived from the GBInSAR monitoring with the geometric information retrieved from the TLS survey was demonstrated as interestingly applicable to the spatial and temporal analysis of the structural stability of monuments subjected to natural/human-induced hazards. The combination of the respective technical features of the two tested techniques allows the limits related to conventional 2D visualization to be overcome, providing a new operational tool to support both ordinary and emergency preservation activities.

The case study of the Domus Tiberiana is highly demonstrative of real situations quite frequently found in archaeological sites open to the public, where the preservation of cultural heritage is coupled by the need of safety conditions for visitors and operators. The monitoring data collected in almost one year did not show significant trends measured along the LOS. Although the obtained results did not lead us to exclude the occurrence of any movements along different directions and/or with major components not actually measurable along the LOS, they were sufficient to reliably suggest a correlation between the observed relative stability and the execution of the recent consolidation works at the base of the Domus Tiberiana. The recognition of different displacement trends during the monitoring period confirmed the capabilities of the integrated methodology to discriminate differential structural behaviour. Hence, an immediate warning was activated whenever the measured displacements appeared suspicious and potentially anticipating the evolution into severe damages. The examples of preventive detection here discussed highlight the analytical specificity of the GBInSAR technique, improved by the contribution of the TLS.

These encouraging results open promising perspectives for further applications on similar cultural heritage contexts, as well as on different typologies of structures, like bridges, towers and masonries sticking out from the ground with high elevation of the architecture, which can be affected by a huge variety of instability mechanisms (e.g., tendency to toppling, wind-induced structural responses, seismic amplification effects). Such phenomena can be particularly hazardous in case of absence or partial/total damage of the former connecting architectural elements. The employment of the GBInSAR – TLS integrated approach might clarify the kinematics of the movements and facilitate simulations of the most probable instability mechanisms, with associated estimation of the direct/indirect impacts on the conservation. Future advances in research can be the use of the GBInSAR data for modelling the structural behaviour of the monitored surfaces, to reliably predict the response to stresses and, consequently, plan appropriate countermeasures.

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